

Superconducting Solenoids for the Muon Cooling Cells

The beam bunching and cooling section is between phase-rotation section that ends at $z = 356$ meters (down stream from the target) and the linear accelerator section that starts at $z = 527$ meters. The bunching section starts with a matching section that is about 8-meters long. This section matches the phase-rotation induction of 1.25 T with the field flipping structure that characterizes the bunching and cooling sections. Downstream from the matching section are twenty cells of beam bunching. Each cell is 2.75 m long and each cell contains four 201.25 MHz RF cavities and one 402.5 MHz RF cavity. The beam-bunching section starts at $z = 364$ m and ends at $z = 419$ m. The beam-bunching section is followed by seventeen cells of muon cooling that are 2.75-m long. These cells have four 201.25 MHz RF cavities and a hydrogen absorber that is in the bore of the field flip solenoid. The long cell cooling section extends from $z = 419$ m to $z = 465$ m. The final cooling section consists of thirty-seven cells that are 1.65-meters long. The 1.65-meter long cooling cells contains two 210.25 MHz RF cavities and a short hydrogen absorber that is in the field flip solenoid. The short cell cooling channel extends from $z = 465$ meters to $z = 527$ meters.

The matching section consists of two 2.75-meter long cells and about 2.5 meters of solenoids that have a warm bore diameter of 600 mm. These solenoids must be designed to withstand longitudinal forces of up to 60 metric tons that are imparted on them by the two matching cells downstream. The solenoids in the matching section cells are the same as in the cells in the beam bunching section. The twenty 2.75-meter long bunching cells are the same as the 2.75-meter long cooling cells. The warm bore aperture of the of the A coils for a 2.75-meter long cooling cell must be about 650 mm in order to accommodate a liquid hydrogen absorber. The warm bore aperture for the beam bunching cell flux reversal coils must be the same in order to accommodate a 402.5 MHz RF cavity. Room temperature service ports to the 402.5 MHz RF cavity can go out through the flux reversal magnet cryostat between the flux reversal coils. (See coils A in Figure 1.) Table 1 below shows the number of cells of each type, the minimum aperture requirements for the magnets and the maximum coil current densities for the coils in each cell type. Included in Table 1 is the magnetic field 9.9 meters from the beam axis. Because the bunching and cooling cell solenoids are constantly changing polarity, there is almost no stray field from these solenoids at $R = 10$ meters.

Magnet parameters and a magnet cross-section for the 2.75-meter long bunching and cooling cell magnets are shown in Table 2 and Figure 1. Note: the solenoids in the 2.75-meter long cells are the same for both bunching and cooling cells. Magnet parameters and a magnet cross-section for the 1.65-meter long cooling cell magnets are shown in Table 3 and Figure 2. The solenoid magnet cross-sections shown in Figures 2 and 3 are through the longitudinal supports. The penetration of the hydrogen absorber plumbing through the space between the A coils is not shown in Figures 1 and 2.

Table 1. Basic Cell Parameters for the Beam Bunching and Cooling Cell

| Parameter | 2.75 m Cell | 1.65 m Cell |
|---|-----------------------|-----------------------|
| Number of Cells of This Type | 39 | 37 |
| Cell Length (mm) | 2750 | 1650 |
| Maximum Space for the RF Cavity | 1966 | 1108 |
| Number of 201.25 MHz RF Cavities per Cell | 4 | 2 |
| Number of 402.5 MHz RF Cavities per Bunching Cell | 1 | NA |
| A Magnet Cryostat Length (mm) | 784 | 542 |
| B Magnet Cryostat Length (mm) | 283 | 209 |
| Aperture for the A Magnet (mm) | 650 | 370 |
| Aperture for the B Magnet (mm) | 1390 | 1334 |
| Maximum A Coil Current Density ($A\ mm^{-2}$) | 128.04 | 99.65 |
| Maximum B Coil Current Density ($A\ mm^{-2}$) | 99.24 | 109.45 |
| Maximum Cell Stored Energy (MJ) | 13.2 | 17.6 |
| Maximum Longitudinal Warm to Cold Force (MN) | 0.74 | 1.20 |
| Number of Longitudinal Supports per Coil | 4 | 6 to 8 |
| Peak Induction 9.9 m from the Cell axis (T) | 1.18×10^{-5} | 2.62×10^{-5} |

| | A Magnets | B Magnets |
|--|-----------------------|-----------------------|
| Physical Parameters | | |
| Magnet Cryostat Length (mm) | 784 | 283 |
| Magnet Cryostat Bore Diameter (mm) | 650 | 1390 |
| S/C Coil Length (mm) | 167 | 162 |
| Inner Radius of the Coil (mm) | 355 | 729 |
| S/C Coil Thickness (mm) | 125 | 162 |
| Distance Between Coils in Z Direction (mm) | 350 | NA |
| Inner Support Structure Thickness (mm) | 15 | 0 |
| Outer Support Structure Thickness (mm) | 20 | 25 |
| Number of Turns per Magnet | 2304 | 1472 |
| Magnet Cold Mass (kg) | 1430 | 1245 |
| Magnet Overall Mass (kg) | 1870 | 1570 |
| Critical Parameters and Magnetic Forces | | |
| Maximum Magnet Design Current (A) | 2320.2 | 1779.9 |
| Peak Induction in the Windings (T) | 7.5 | 6.5 |
| Magnet Stored Energy at Design Current (MJ) | ~7.9 | ~7.7 |
| Magnet Self Inductance per Cell (H) | ~2.9 | ~4.9 |
| Superconductor Matrix J (A mm ⁻²) | 155 | 119 |
| E J ² Limit per Magnet Cell (J A ² m ⁻⁴) | 1.89x10 ²³ | 1.09x10 ²³ |
| Force Pushing the A Coils Apart (metric tons) | 329 | NA |
| Peak Fault Force on a the Coil (metric tons) | 75.3 | 75.3 |



Table 3. Solenoid Parameters for the 1.65-meter Long Cooling Cell

| | A Magnets | B Magnets |
|--|-----------------------|-----------------------|
| Physical Parameters | | |
| Magnet Cryostat Length (mm) | 542 | 209 |
| Magnet Cryostat Warm Bore Diameter (mm) | 380 | 1334 |
| S/C Coil Length (mm) | 145 | 109 |
| Inner Radius of Inner Coil | 210 | 687 |
| S/C Coil Thickness (mm) | 138 | 326 |
| Distance Between Coils in Z Direction (mm) | 132 | NA |
| Inner Support Structure Thickness (mm) | 20 | 0 |
| Center Support Structure Thickness (mm) | 30 | NA |
| Outer Support Structure Thickness (mm) | 40 | 25 |
| Number of Turns per Magnet | 4480 | 1974 |
| Magnet Cold Mass (kg) | 1995 | 1750 |
| Magnet Overall Mass (kg) | 2430 | 2290 |
| Electrical Parameters and Magnetic Forces | | |
| Maximum Magnet Design Current (A) | 1780.5 | 1896.7 |
| Peak Induction in the Windings (T) | 8.4 | 6.5 |
| Magnet Stored Energy at Design Current (MJ) | ~10.7 | ~11.0 |
| Magnet Self Inductance per Cell (H) | ~6.8 | ~6.1 |
| Superconductor Matrix J (A mm ⁻²) | 119 | 126 |
| E J ² Limit per Magnet Cell (J A ² m ⁻⁴) | 1.51x10 ²³ | 1.74x10 ²³ |
| Force Pushing the A Coils Apart (metric tons) | 1980 | NA |
| Peak Fault Force on a the Coil (metric tons) | 122 | 122 |

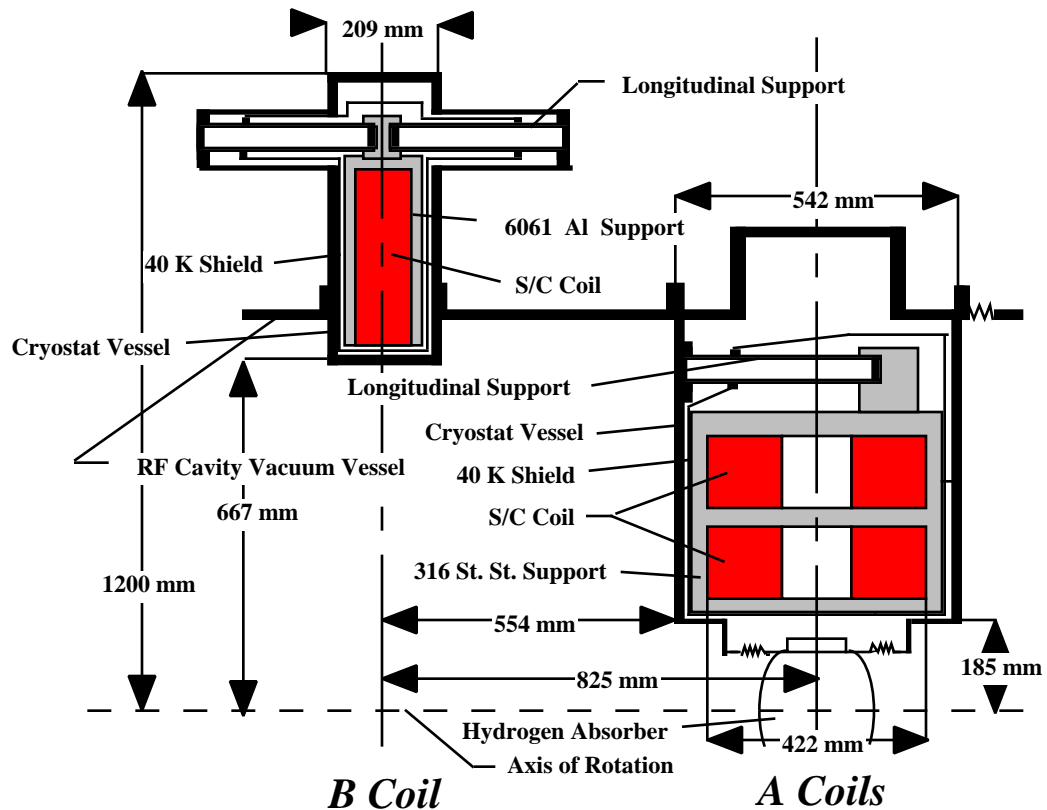


Figure 2. Magnet Cross-section for the 1.65-meter Long Cooling Cell

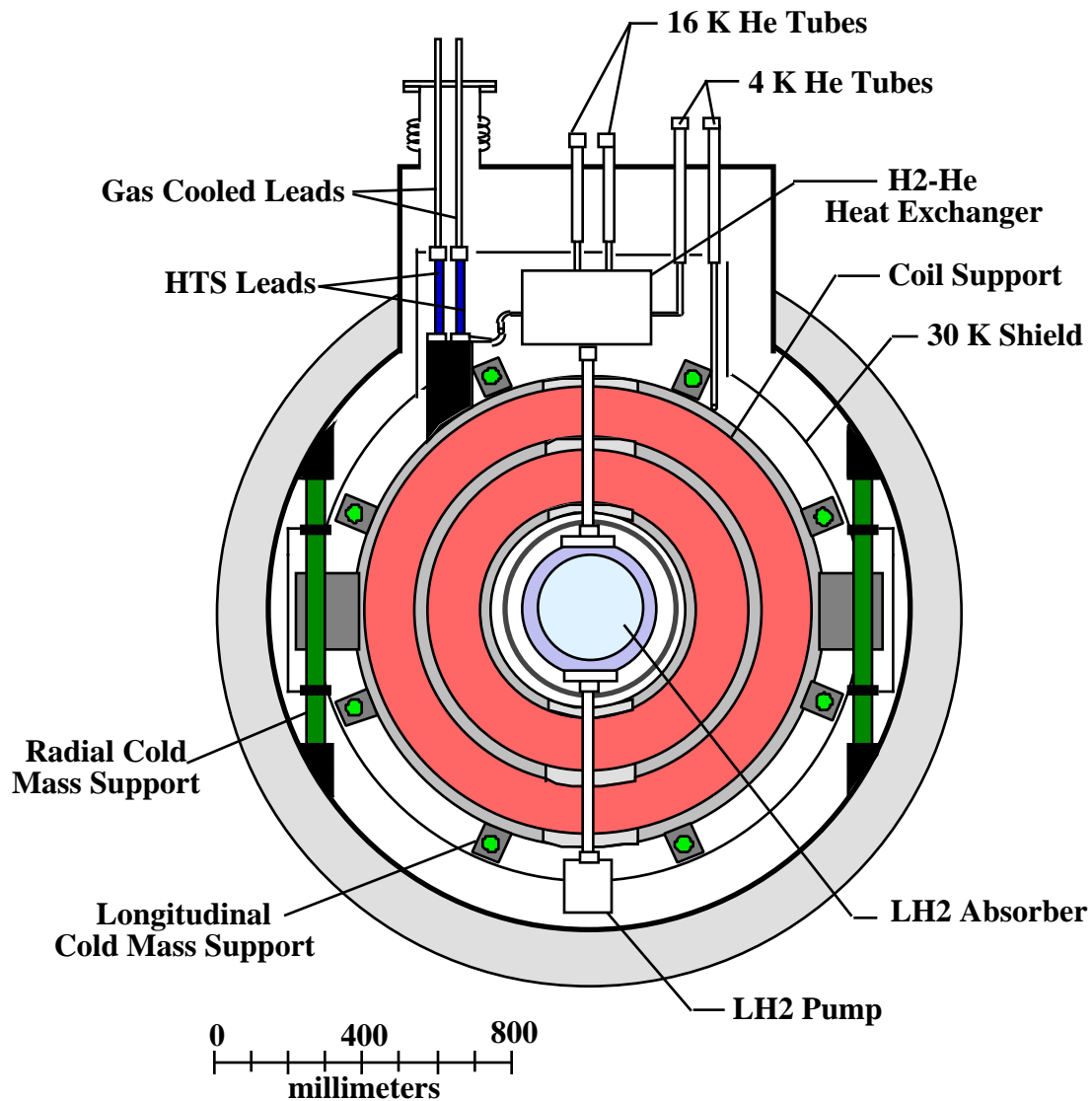


Figure 3. A Cross-section of the 1.65 m Cell A Magnet Perpendicular to the Beam

Figures 1 and 2 show a cross-section of the bunching and cooling cell solenoids. The plane for the cross-sections is taken through the warm to cold supports that carry axial forces. The cross-sections in Figures 1 and 2 show the magnet cryostats, the coils, the coil support structure, the 30 K shields, and the vacuum vessel around the RF cavities. The cryostat vacuum systems are separated from the vacuum around the RF cavities and the beam vacuum. Figure 3 shows a cross-section through the center of the 1.65-meter long cell A coil pair. Figure 3 shows the location of the longitudinal cold mass supports and the cold mass supports that carry forces in both directions perpendicular to the solenoid axis. Figure 3 illustrates how magnet electrical leads, and helium refrigeration can be brought into the cryostat. Figure 3 is a typical cross-section that can be applied to all of the bunching and cooling cell solenoids.

Figures 1 and 2 show the location of the hydrogen absorbers within the bore of the A coil pair. The hydrogen absorber will share the same cryostat with the A coils. The hydrogen absorber and the A magnet will have a common vacuum and the hydrogen absorber will be supported from the A coil package by a low thermal conductivity support system made from a titanium tube. Figure 3 illustrates schematically that connections to the hydrogen absorber can be made between the A coils through the support structure that carries the magnetic large forces generated by the two A coils that operate at opposing polarities.

Forces in the longitudinal direction are a serious concern for the bunching and cooling solenoids. The field flip coils (the A coils) generate large forces (up to 1950 metric tons) pushing them apart. These forces must be carried by a 4.4 K metallic structure between the two coils. The magnitude of the forces pushing the A coils apart depends on the spacing between the coils, the average coil diameter and the current carried in each coil. The inter-coil coil forces are carried by either aluminum or stainless steel shells on the inside and the outside of the coils. The forces are transmitted to the coil end plates, which are put in bending. Large stresses are developed at the point where the end plates meet the shells inside and outside the coils. The force between the A coils in the 1.65-meter long cooling cells is so large (about 1950 metric tons), the A coils had to be divided in the radial direction in order to reduce the bending stress in the end plates. The large stress in the end plates of the A coils in the 1.65-meter long cooling cell dictate that the end plates and shells around the A coils must be made from 316 stainless steel.

If the currents in all of the A coils and all of the B coils were the same from cooling cell to cooling cell, there would be no net longitudinal force on any of the coils. The currents in the cooling cell coils vary as one goes down the bunching and cooling channel. This generates a longitudinal force in various magnet coils. The largest longitudinal forces will be generated at the ends of the string or when one coil quenches and adjacent coils do not quench. One can attach all of the coils together with cold members, but further examination suggests that this approach does not make sense if one wants to be able to assemble and disassemble the muon cooling system. As a result, every magnet is assumed to have cold to warm longitudinal supports. The cold to warm supports in the magnets in the 2.75-meter long cells are designed to carry 80 metric tons (the maximum force during a magnet fault). These forces can be carried by four oriented glass fiber epoxy cylindrical supports that are 50-mm in diameter with a 4-mm thick wall. Oriented glass fiber rods can carry stresses up to 600 MPa in either tension or compression.

The 1.65-meter long cell magnets have longitudinal cold to warm supports that are designed to carry 120 metric tons. Figure 3 shows the location of eight of these supports on the 1.65-meter long cell A magnet. A six support longitudinal support system would also be practical. The support shown for the A coil in Figure 2 is designed to operate in both tension and compression. Further engineering can define an optimum cold mass support system for these magnets. Compared to other heat loads into the magnets, the longitudinal cold mass supports represent about one quarter of the total heat leak into the magnet cryostat.

The magnet conductor that is assumed for all of the B solenoids is a conductor that is 7 parts copper and 1 part niobium-titanium. This conductor consists of strands of conductor with a copper to superconductor ratio of 1 to 1.3. The twist pitch in the superconductor is about 10 mm. The strands of this conductor are attached to a pure copper matrix. The overall dimensions for the finished conductor is 3 mm by 5 mm. The proposed conductor will carry 5100 A at 5 T and 4.2 K. At 7.5 T, the proposed conductor will carry about 2500 A at 4.4 K. This conductor could be used in the 2.75-meter cell A coils but the margin is rather tight. The problem occurs in the 1.65-meter long cell A magnet where the peak field at the high field point in the magnet is 8.4 T. This coil must be operated at reduced temperature (say 2.5 K) when the proposed conductor is used. A re-optimization of the short cooling cell that moves the A coils further apart may be a better solution to the high field problem in the short cell A coils. It is proposed that the A coils in the both types of cells use a conductor with a 4 to 1 copper to superconductor ratio.

The conductor is assumed to have a varnish insulation that is 0.05 mm thick. The layer to layer fiber glass epoxy insulation is assumed to be 0.4 mm thick. The ground plane insulation around the coils is assumed to be 1.6 mm thick. This permits the superconducting coils to be discharged with a voltage across the leads of up to 1200 volts. Each A coil set and each B coil is assumed to be powered separately. A quench protection voltage of 1200 V is adequate to protect any of the coils in the cooling cells. Because the conductor current density is high, the A coils in the 2.75-meter long cells have the smallest safety margin when it comes to quench protection. Re-optimization of these coils can improve their quench protection.

The conductor current and current density given for the A and B coils in Tables 2 and 3 are the peak values that would occur in the cells operating at the highest current. The estimated stored energy given in tables 2 and 3 occur at the peak design current in the coils. In general, when the current density is high in the A coil, the current density in the B coil is low. The stored energy for the cooling cells changes very little as one moves down the cooling channel. The cell stored-energy shown in Table 1 is the average stored energy for that type of cell. Table 4 on the next page shows the average coil current density and coil current for the A and B coils in the various regions of the bunching and cooling channel.

Table 4. Coil Average J and Coil I for various Sections of the Bunching and Cooling Channel

| Section | No. Cells | A Coil J(A mm ⁻²) | A Coil I (A) | B Coil J (A mm ⁻²) | B Coil I (A) |
|----------------|-----------|-------------------------------|--------------|--------------------------------|--------------|
| Bunching Cells | 22 | 106.34 | 1927.0 | 99.24 | 1779.9 |
| Cooling 1-1 | 5 | 106.34 | 1927.0 | 99.24 | 1779.9 |
| Cooling 1-2 | 6 | 117.83 | 2135.3 | 92.42 | 1657.8 |
| Cooling 1-3 | 6 | 128.04 | 2320.2 | 84.75 | 1520.0 |
| Cooling 2-1 | 14 | 82.21 | 1468.8 | 109.45 | 1896.7 |
| Cooling 2-2 | 10 | 89.68 | 1602.3 | 101.93 | 1766.4 |
| Cooling 2-3 | 13 | 99.65 | 1780.5 | 93.47 | 1619.8 |

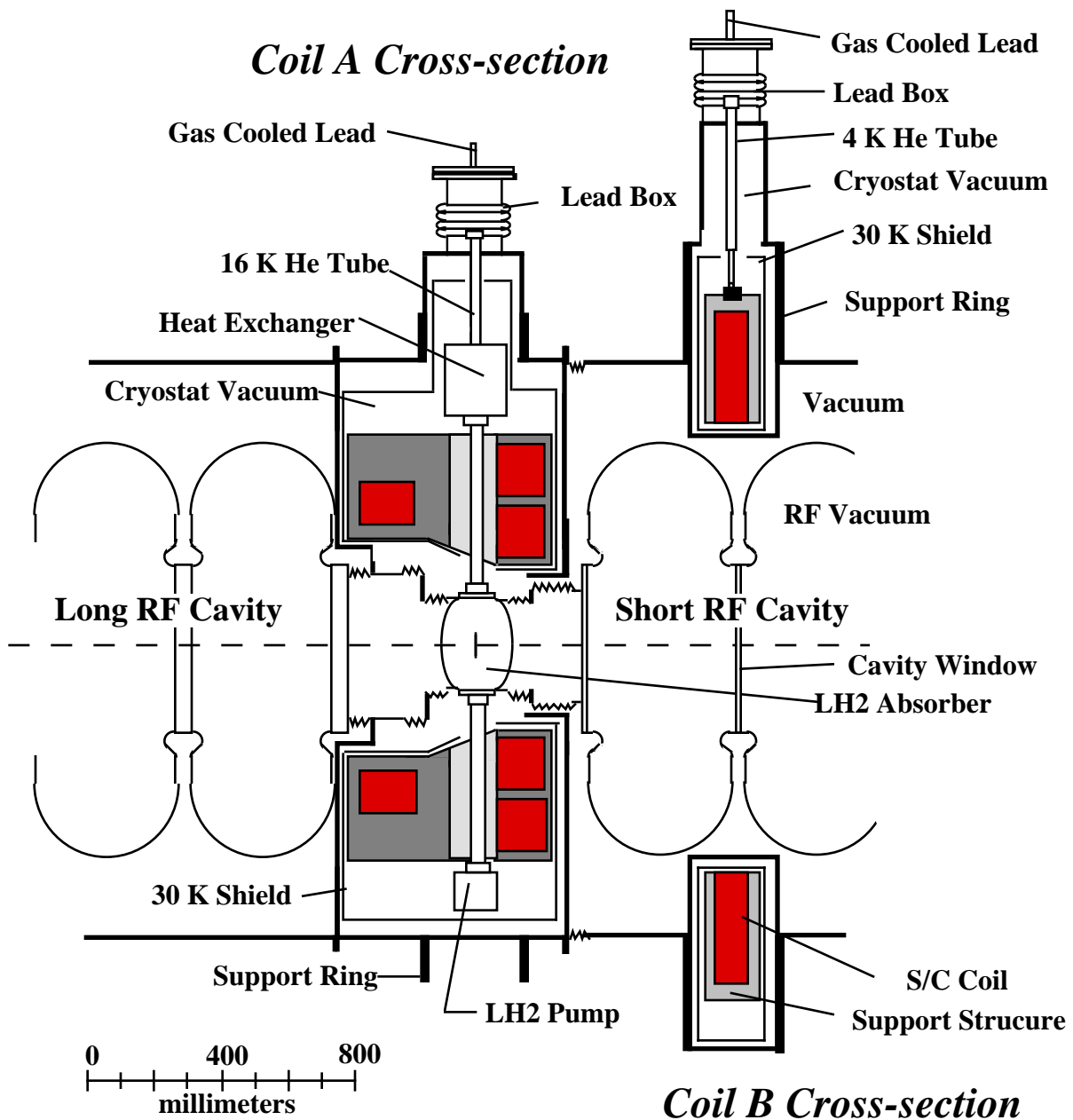


Figure 4. A cross-section of the Matching Region between 2.75 m Cells and 1.65 m Cells

Figure 4 on the previous page is a schematic representation of the matching section of a 2.75-meter long cell to a 1.65-meter long cell. The forces between the coils in the A magnet are quite large. It is assumed that the structure around the A coils is stainless steel. The A coil set shown in Figure 4 is the only unique magnet is the muon cooling channel. There are 39 A and B coils that make up the 2.75-meter long bunching and cooling cells. There are 37 A and B coils that make up the 1.65-meter long cooling cells. Figure 5 below is a schematic representation of the transition between the last cell of the induction linac channel and the first cell of the bunching section transition region. The last two meters of the induction linac channel must have thicker coils with a separate power supply on each coil. The 1.25 T solenoids at the end of the induction cells must have separate longitudinal warm to cold supports to carry forces (up to 60 metric tons) generated by the magnets in the first cells of the bunching section. The longitudinal support members are not shown in Figure 5.

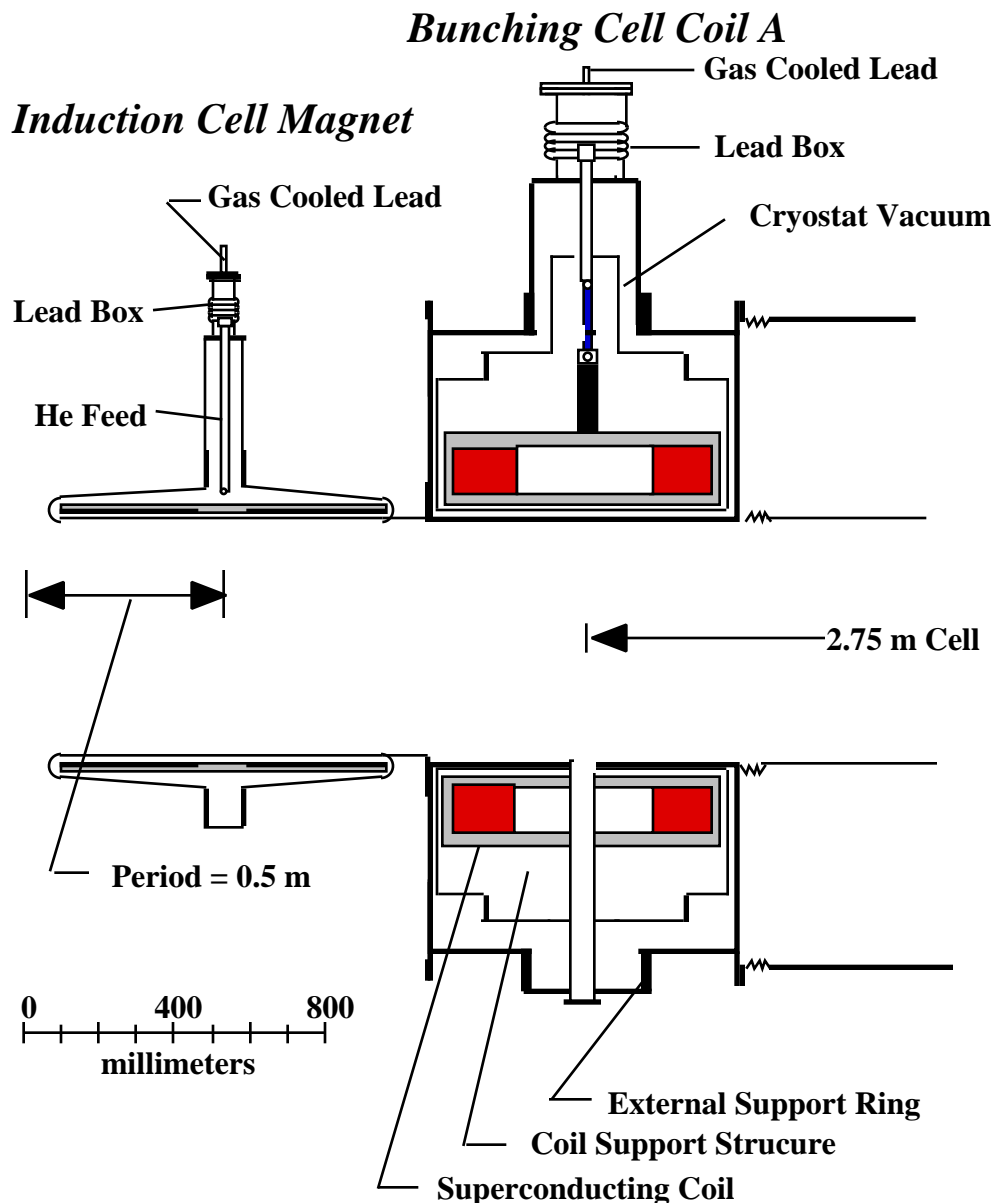


Figure 5. A Cross-section of the Matching Region between Phase Rotation Cells and Bunching Cells

Refrigeration to the muon cooling magnets and hydrogen absorbers is supplied at 16 K and 4.4 K. The 4.4 K refrigeration is used to cool the superconducting coils except for coil A in the 1.65-meter long cell, which is cooled to 2.5 K. The 2.5 K cooling requires an additional heat exchanger and a vacuum pump to produce nearly 0.3 W of cooling at 2.5 K. Most of the heat into the 1.65-meter cell A coil package is intercepted at 4.4 K. The hydrogen absorbers are cooled from the same refrigerator as the solenoid magnets. Refrigeration for the hydrogen absorbers is drawn off at 16 K. The 16 K helium used to cool the liquid hydrogen returns to the helium cold box at 19 K. The absorbers in the 2.75-meter long cell contain 9 liters of liquid hydrogen. The 1.65-meter long cell absorbers contain about 4 liters of liquid hydrogen. The estimated heat load to the absorbers is between 120 and 130 W. Table 5 below shows the refrigeration requirements for the 2.75-meter long cells and the 1.65-meter long cells with hydrogen absorbers. The equivalent 4.4 K refrigeration reflects the Carnot ratios from 4.4 K to 16 K and the refrigeration lost when helium returns to the compressor by bypassing the refrigerator heat exchangers. The equivalent 4.4 K refrigeration for each of the 22 bunching cells is 21.1 W per cell. About 10.4 W of equivalent 4.4 K refrigeration is used to cool two pairs of 2000 A gas-cooled leads from 40 K to 300 K.

Table 5. The Sources of Heat at 4.4 K, 20 K and 35 K in the Bunching and Cooling Cell Magnets

| Source of Heat | 2.75 m Cell (W) | | 1.65 m Cell (W) | |
|---|-----------------|--------|-----------------|--------|
| | A Coil | B Coil | A Coil | B Coil |
| Magnet Heat Loads at 4.4 K | | | | |
| Vertical Cold Mass Supports | 0.24 | 0.24 | 0.40 | 0.24 |
| Longitudinal Cold Mass Supports | 0.36 | 0.36 | 0.74 | 0.54 |
| Thermal Radiation through MLI | 0.16 | 0.14 | 0.01 | 0.19 |
| Bayonet Joints and Piping | 0.03 | 0.03 | 0.03 | 0.03 |
| Instrumentation Wires | 0.02 | 0.02 | 0.02 | 0.02 |
| HTS Current Leads | 0.60 | 0.60 | 0.60 | 0.60 |
| Total 4.4 K Heat Load per Coil | 1.41 | 1.39 | 1.80 | 1.62 |
| Magnet Heat Loads at 2.5 K | | | | |
| Vertical Cold Mass Supports | --- | --- | 0.05 | --- |
| Longitudinal Cold Mass Supports | --- | --- | 0.10 | --- |
| Thermal Radiation through MLI | --- | --- | 0.11 | --- |
| Bayonet Joints and Piping | --- | --- | 0.01 | --- |
| Instrumentation Wires | --- | --- | 0.00 | --- |
| HTS Current Leads | --- | --- | 0.02 | --- |
| Total 2.5 K Heat Load per Coil | 0.0 | 0.0 | 0.29 | 0.0 |
| Magnet Shield and Intercept Heat Loads at 16 to 40 K | | | | |
| Vertical Cold Mass Supports | 3.8 | 3.8 | 3.8 | 3.8 |
| Longitudinal Cold Mass Supports | 7.2 | 7.2 | 10.8 | 10.8 |
| Thermal Radiation through MLI | 2.7 | 2.9 | 1.9 | 3.2 |
| Bayonet Joints and Piping | 1.3 | 1.3 | 1.3 | 1.3 |
| Instrumentation Wires | 0.1 | 0.1 | 0.1 | 0.1 |
| Gas Cooled Current Leads | --- | --- | --- | --- |
| Total 16 to 40 K Heat Load per Coil | 15.1 | 15.3 | 17.9 | 19.2 |
| Hydrogen Absorber Heat loads (16 K Cooling) | | | | |
| Cold Mass Supports | 1.5 | --- | 1.0 | --- |
| Thermal Radiation through MLI | 0.3 | --- | 0.2 | --- |
| Bayonet Joints and Piping | 1.3 | --- | 1.3 | --- |
| Instrumentation Wires | 0.1 | --- | 0.1 | --- |
| Thermal Radiation to Windows (= 0.2) | 18.4 | --- | 6.9 | --- |
| Beam Absorption Heating | 77.0 | --- | 81.0 | --- |
| Circulation Heater | ~30 | --- | ~30 | --- |
| Total 16 K Heat Load per Coil | 128.6 | 0.0 | 121.5 | 0.0 |
| Equivalent 4.4 K Refrigeration per Cell | 54.6 | | 57.6 | |

Figure 6 shows a schematic representation of the refrigeration for a pair of A coils with a hydrogen absorber. Two phase helium at 4.4 K is used to cool the superconducting coils. If nineteen magnets are cooled from a single flow circuit, the mass flow of two-phase helium should be 8 to 10 grams per second. The flow circuit can have up to 20 magnet coils in series before the helium is returned to the control cryostat. The shields, intercepts, current leads, and hydrogen absorbers are cooled by helium that comes from the refrigerator at 16 K. The helium used to cool the shields and the leads is returned to the refrigerator compress warm. The rest of the 16 K helium returns to the refrigerator at 19 K.

The helium used to cool the magnet shield intercepts heat from the cold mass support, the bayonet tubes, the instrumentation wires and radiation heating through the multi-layer insulation before it is used to cool the gas cooled current leads for the A and B magnet. For the flow circuit shown in Figure 6, the flow helium gas in the shield cooling circuit is dictated by the needs of the gas cooled current-leads. For the current leads in the cooling and bunching magnets this flow varies from 0.15 to 0.23 grams per second. Depending on the needs of the current leads, the temperature rise in the shield gas flow circuit will vary from 14 K to 23 K. If one could optimize the magnets, the lead current might be as low as 1200 A. With 1200 A current leads the temperature at the top of the high T_c superconducting leads would be about 50 K. It is proposed that both the A and the B magnet shields be cooled using the same 16 K source of gas from the helium refrigerator, but this is not optimum from the standpoint of overall refrigeration system efficiency. When the helium refrigerator cools both the hydrogen absorber and the magnets, there will be enough excess refrigeration capacity available to cool down the magnet coils down in a reasonable time.

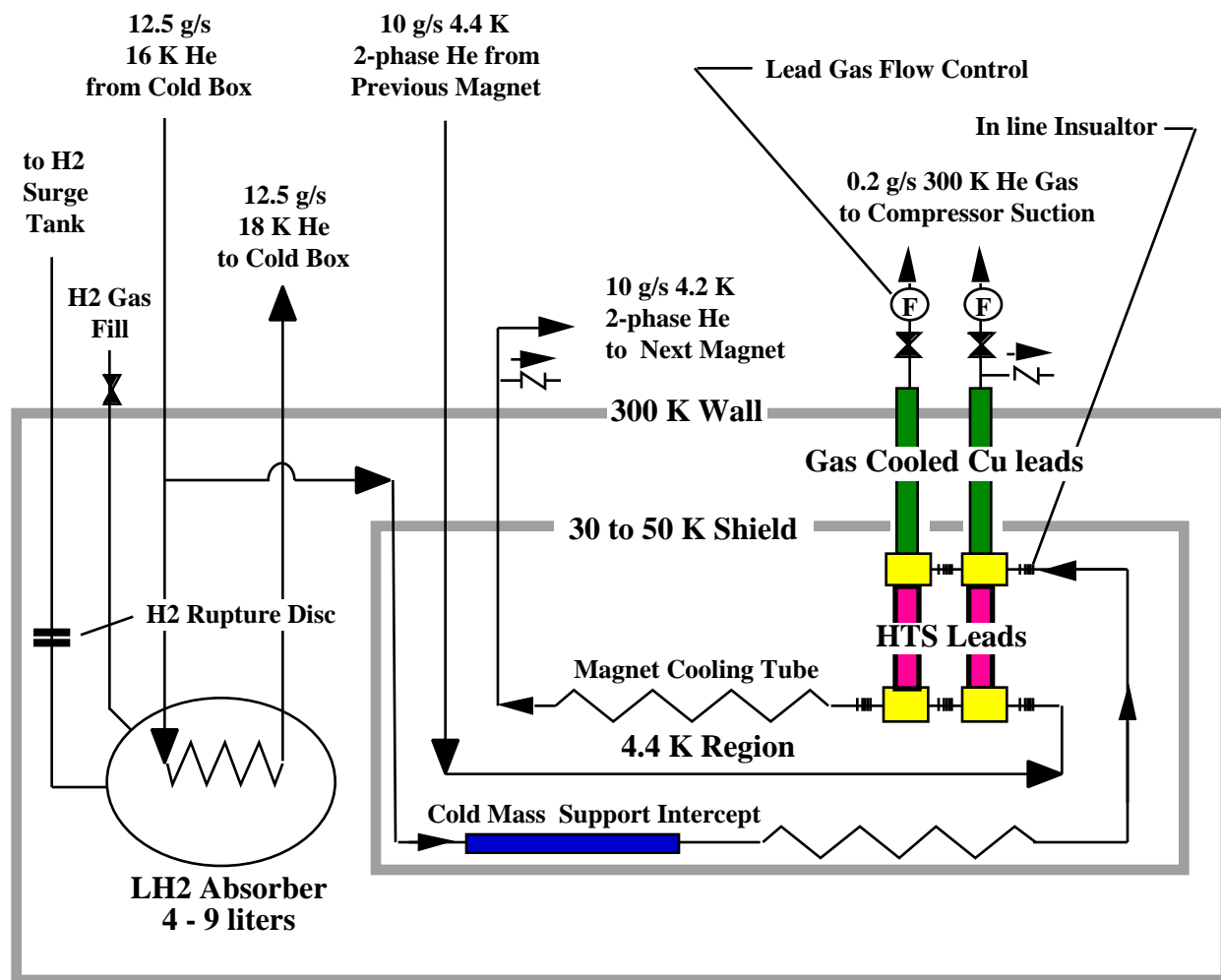


Figure 6. Cryogenic Cooling System within a Typical Cooling A Coil Cryostat

The flow in the 16 K circuit to the hydrogen absorber is dictated by the heat load in the absorber. Without a muon beam, the heat load could be as low as 22 W. With beam heating and the circulation heater operating the heat load into the absorbers can approach 130 W. The temperature rise in the absorber cooling helium circuit should be limited to about 2 K. As a result, the helium flow circuit used to cool the hydrogen absorbers should be designed to provide 12.5 grams per second of 16 K helium. This gas will be returned to the refrigerator cold box at around 19 K (including heating in the return transfer line).

The bunching section has twenty magnets and twenty-one B magnets that have the same current in the coils. The number of cooling section cells where magnets carry the same current is up to thirteen. It is assumed that each magnet in the bunching and cooling sections has its own leads. The magnets can be powered individually or in strings of magnets that carry the same current. Powering magnets as a string of magnets requires a more complicated quench protection system that uses diodes and resistors to cause the string current to by-pass the quenching magnet. For simplicity sake, it is assumed that each magnet has its own power supply and quench protection system. A 2500 A power supply for charging and discharging a single magnet coil (either an A coil or a B coil) should be capable of developing ± 7 volts. The magnet quench protection consists of a dump resistor across the magnet leads. When a quench is detected, a fast switch disconnects the power supply from the magnet. In all cases, the power supply control system should permit one to control the current and the voltage across the coils as the magnet is charged and discharged. The power supply is not required to operate at both positive and negative currents. A controller is used to control the charging and discharging voltages across each coil and regulate the current once the coil has reached its set current.

The B coils can be aligned so that the solenoid axis is correct to 0.3 m-radians. The magnetic center of the B coil can be maintained to about 0.3 mm. The alignment of the A coils can probably be maintained to about 0.5 or 0.6 m-radians. Correction dipoles can be installed in the bore of the A coils that will permit the apparent solenoid axis to be corrected by ± 1.5 m-radians.